

A Long, Cold, Early r -process? ν -induced Nucleosynthesis in He Shells Revisited

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We revisit a ν -driven r -process mechanism in the He shell of a core-collapse supernova, finding that it could succeed in early stars of metallicity $Z \lesssim 10^{-3} Z_{\odot}$, at relatively low temperatures and neutron densities, producing $A \sim 130$ and 195 abundance peaks over ~ 10 –20 s. The mechanism is sensitive to the ν emission model and to ν oscillations. We discuss the implications of an r -process that could alter interpretations of abundance data from metal-poor stars, and point out the need for further calculations that include effects of the supernova shock.

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While the basic features of the rapid-neutron-capture or r -process have been known for over 50 years [1], the search for the specific astrophysical site has frustrated many researchers [2]. The situation has continued despite a growing set of observational constraints, including elemental abundances from metal-poor (MP) stars [3], that appear to favor core-collapse supernovae (SNe) and to disfavor some otherwise attractive sites, such as neutron star mergers (NSMs) [4, 5].

The surface compositions of old MP stars provide a fossil record of nucleosynthesis and chemical enrichment in the early Galaxy. For ultra-metal-poor (UMP) stars, where $[\text{Fe}/\text{H}] \equiv \log(\text{Fe}/\text{H}) - \log(\text{Fe}/\text{H})_{\odot} \lesssim -3$, surface enrichments should reflect contributions from just a few nearby nucleosynthetic events. The data show that the r -process operated in the early Galaxy with a frequency consistent with SNe from short-lived massive progenitors. Many MP stars, including several UMP ones, also exhibit a solar-like abundance pattern of heavy r -process elements (r -elements) for $A > 130$ [3].

The similarity between the MP-star and solar r -patterns tempts one to conclude that there is a unique site for the r -process, operating unchanged over the Galaxy's history (cf. [6]). But is this the case? Epstein, Colgate, and Haxton (ECH) [7] suggested a possible r -site some years ago that would complicate such an interpretation. The ECH mechanism utilizes neutrons produced by neutral-current (NC) ν reactions in the He zones of certain low-metallicity SNe. The proposed sequences are ${}^4\text{He}(\nu, \nu n){}^3\text{He}(n, p){}^3\text{H}({}^3\text{H}, 2n){}^4\text{He}$ and ${}^4\text{He}(\nu, \nu p){}^3\text{H}({}^3\text{H}, 2n){}^4\text{He}$. For temperatures $\lesssim 3 \cdot 10^8$ K, the neutrons thus produced will not reassemble into ${}^4\text{He}$ by reactions involving light nuclei. Nor will they be captured by ${}^4\text{He}$ as ${}^5\text{He}$ is unbound. Instead, they will be efficiently captured by seed nuclei, such as ${}^{56}\text{Fe}$, present in the birth material of the SN. The ECH neutron source is primary and provides a roughly fixed number of neutrons. For MP progenitors there are few Fe seeds and thus enough neutrons per seed to produce heavy r -elements. As the metallicity of the SN increases,

the neutron/seed ratio decreases, limiting the production of r -elements to low A and eventually stopping the production altogether. That is, the ECH mechanism turns off with increasing metallicity.

The ECH mechanism was proposed as a candidate general r -process, and thus was critiqued in Ref. [8] for being viable only in low-metallicity, compact SNe. Subsequent re-examination of the mechanism focused on NC ν reactions only, either confirming earlier results or finding no significant production of $A > 80$ nuclei without assuming ad hoc conditions in outer He zones [9]. In this Letter we show that the charged-current (CC) reaction ${}^4\text{He}(\bar{\nu}_e, e^+ n){}^3\text{H}$ can be an efficient neutron source for a successful low-metallicity ECH mechanism using recently generated models of MP massive stars [10]. Because other candidate r -sites, such as NSMs, may turn on at higher metallicity, it is clearly important to explore any mechanism that might account for the r -elements generated at earlier times. Furthermore, as we have so far failed to identify “the r -process,” it would be a step forward to identify “an r -process,” even if the mechanism operated only for a limited time.

An r -process requires neutron densities $n_n \gtrsim 10^{18}$ /cm³, so that neutron capture will be fast compared to β decay, and a neutron/seed ratio $\gtrsim 80$, so that heavy r -elements can be produced from seeds like ${}^{56}\text{Fe}$. These requirements lead us to examine the outer He shells of MP massive stars, where the low abundances of nuclei like ${}^{12}\text{C}$, ${}^{14}\text{N}$, and ${}^{16}\text{O}$ make iron-group nuclei an important neutron sink. (The higher temperatures found in the inner He zone, $\sim 3 \cdot 10^8$ K, lead to significant ${}^{12}\text{C}$ and ${}^{16}\text{O}$ production by He burning, regardless of metallicity. As we discuss later, a modified ECH mechanism may operate in such an environment, with ν -induced neutrons “banked” in ${}^{13}\text{C}$ and ${}^{17}\text{O}$, then liberated on shock wave passage.)

We use models u11–u75 of 11–75 M_{\odot} stars with an initial metallicity $Z = 10^{-4} Z_{\odot}$ (Z being the total mass fraction of elements heavier than He) presented in Ref. [10]. The outer He shells of these models are at radii $r \sim$

10^{10} cm, for which the gravitational collapse time is

$$\tau_{\text{coll}} \sim \frac{1}{\alpha} \sqrt{\frac{r^3}{2GM}} \sim 102 \left(\frac{0.6}{\alpha} \right) \left(\frac{M_{\odot}}{M} \right)^{1/2} r_{10}^{3/2} \text{ s}, \quad (1)$$

where $\alpha \sim 0.6$ is the ratio of the infall velocity to the free-fall velocity, $M \sim 2.4\text{--}33 M_{\odot}$ is the mass enclosed within r , and r_{10} is r in units of 10^{10} cm. For such large τ_{coll} , we can assume that the radius, density, and temperature of the He-shell material stay constant before the SN shock arrives. We take the time of shock arrival to be approximately given by the Sedov solution [8]

$$\tau_{\text{sh}} \sim 21.8 \left(\frac{M - M_{\text{NS}}}{M_{\odot}} \right)^{1/2} \frac{r_{10}}{E_{50}^{1/2}} \text{ s}, \quad (2)$$

where $M_{\text{NS}} \sim 1.4 M_{\odot}$ is the mass of the neutron star produced by the core collapse and E_{50} is the explosion energy in units of 10^{50} ergs. Following the passage of the shock, both the temperature and density of the material first increase rapidly and then decrease on timescales comparable to τ_{sh} . The peak temperature (in units of 10^8 K) of the shocked material is [8]

$$T_{p,8} \sim 2.37 E_{50}^{1/4} r_{10}^{-3/4}. \quad (3)$$

For such low temperatures, photo-dissociation of heavy nuclei will not occur [8]. Other effects of shock-wave passage are helpful to the r -process (see discussion below).

During the several seconds following core collapse, an intense flux of ν s irradiates the He zone. While the zone's radius, density, and temperature are unchanged, ν reactions must induce and maintain a free-neutron density $n_n \gtrsim 10^{18}/\text{cm}^3$ to drive an r -process. We take the ν luminosity to be $L_{\nu}(t) = L_{\nu}(0) \exp(-t/\tau_{\nu})$ for each of the six flavors, with $L_{\nu}(0) = 1.67 \cdot 10^{52}$ erg/s and $\tau_{\nu} = 3$ s, so that the total energy carried off by ν s is $3 \cdot 10^{53}$ ergs. We use Fermi-Dirac ν spectra with zero chemical potential. We adopt nominal temperatures T_{ν_e} , $T_{\bar{\nu}_e}$, and T_{ν_x} of 4, 5.33, and 8 MeV, respectively, where ν_x stands for any heavy flavor, but explore the temperature dependence. Our nominal parameters are typical of earlier SN models (e.g., [11]). The spectra at the He zone will be affected by ν oscillations [12], as the ν mass splitting $|\delta m_{13}^2| \sim 2.4 \cdot 10^{-3} \text{ eV}^2$ produces a level crossing for a 20 MeV ν at $\rho \sim 1.6 \cdot 10^3 \text{ g/cm}^3$, a density characteristic of the carbon zone. The consequences for the r -process depend critically on the assumed ν mass hierarchy.

We evaluated the nucleosynthesis for models u11–u75 and for various ν oscillation scenarios. As an example of a successful r -process, we present detailed results for zone 597 of u11, assuming an inverted ν mass hierarchy (IH, full $\bar{\nu}_e \leftrightarrow \bar{\nu}_x$ conversion). Zone parameters are $r_{10} = 1.10$, $M = 2.43 M_{\odot}$, $\rho = 50.3 \text{ g/cm}^3$, and $T_8 = 0.848$. The zone is nearly pure ${}^4\text{He}$: the initial mass fractions of ${}^{12}\text{C}$ and ${}^{14}\text{N}$ are $X_{12} \sim 1.39 \cdot 10^{-5}$ and $X_{14} \sim 1.35 \cdot 10^{-6}$. The total mass fraction of $A \geq 16$ nuclei is $\sim 3.52 \cdot 10^{-7}$

($\sim 3.15 \cdot 10^{-8}$ from ${}^{56}\text{Fe}$). A big bang nucleosynthesis network [13] was modified to follow the ECH mechanism, with NC and CC ν cross sections taken from Ref. [14], which agree well with those of Ref. [7]. As the network stops at ${}^{16}\text{O}$, neutron capture on $A \geq 16$ nuclei was approximated by a constant loss rate corresponding to the initial abundances of such nuclei. As discussed below, the evolution of the neutron number fraction Y_n is not significantly altered by neglecting changes in the $A \geq 16$ composition.

Figure 1a, the number-fraction evolution with time t , can be readily understood: (1) The extremely efficient reaction ${}^3\text{He}(n, p){}^3\text{H}$ immediately consumes all neutrons produced by the NC reaction ${}^4\text{He}(\nu, \nu n){}^3\text{He}$. Each NC reaction thus yields one proton and one ${}^3\text{H}$. (2) The neutron-producing reaction proposed by ECH, ${}^3\text{H}({}^3\text{H}, 2n){}^4\text{He}$, is inefficient. Instead, ${}^3\text{H}$ is destroyed by abundant ${}^4\text{He}$ via ${}^3\text{H}({}^4\text{He}, \gamma){}^7\text{Li}$. Neutron restoration by ${}^7\text{Li}({}^3\text{H}, 2n){}^2{}^4\text{He}$ is ineffective for the conditions of Figure 1a. (3) Neutron production is dominated by the CC reaction ${}^4\text{He}(\bar{\nu}_e, e^+ n){}^3\text{H}$. (4) The principal neutron sinks are ${}^7\text{Li}$, ${}^{12}\text{C}$, and $A \geq 16$ nuclei. (5) Protons are not a significant neutron sink as $p(n, \gamma){}^2\text{H}$ is immediately followed by ${}^2\text{H}({}^3\text{H}, n){}^4\text{He}$. (6) Due to its small initial abundance, neutron capture by ${}^{14}\text{N}$ is also negligible.

The rate of the CC $\bar{\nu}_e$ reaction per ${}^4\text{He}$ nucleus is

$$\lambda_{\bar{\nu}_e \alpha}^{\text{CC}}(t) = \frac{2.28 \times 10^{-7}}{r_{10}^2 \exp(t/\tau_{\nu})} \left(\frac{T_{\bar{\nu}_e}}{6 \text{ MeV}} \right)^k \text{ s}^{-1}, \quad (4)$$

where $k \sim 6.26$ and ~ 5.17 for $T_{\bar{\nu}_e} = 4\text{--}6$ and $6\text{--}8$ MeV, respectively. Based on the above discussion, Y_n in Figure 1a can be estimated from

$$\dot{Y}_n = \lambda_{\bar{\nu}_e \alpha}^{\text{CC}}(0) Y_{\alpha} \exp(-t/\tau_{\nu}) - \lambda_{n, \gamma} Y_n(t), \quad (5)$$

where $\lambda_{\bar{\nu}_e \alpha}^{\text{CC}}(0) = 8.35 \cdot 10^{-7}/\text{s}$ for $T_{\bar{\nu}_e} = 8$ MeV (IH), $Y_{\alpha} \sim 1/4$ is the number fraction of ${}^4\text{He}$, and $\lambda_{n, \gamma} \sim 8.12 \times 10^{-2}/\text{s}$ is the net rate of neutron capture on ${}^7\text{Li}$ (46.2%), ${}^{12}\text{C}$ (21.9%), and $A \geq 16$ nuclei (31.9%). We find, in good agreement with Figure 1a,

$$Y_n(t) = \frac{\lambda_{\bar{\nu}_e \alpha}^{\text{CC}}(0) Y_{\alpha} \tau_{\nu}}{1 - \lambda_{n, \gamma} \tau_{\nu}} [\exp(-\lambda_{n, \gamma} t) - \exp(-t/\tau_{\nu})]. \quad (6)$$

The neutron number density in zone 597 of u11, $n_n = Y_n \rho N_A \sim 10^{19}/\text{cm}^3$ where N_A is Avogadro's number, is sufficient to drive an r -process (see Figure 2). The most effective seed is ${}^{56}\text{Fe}$ as it is above the $N = 28$ closed neutron shell. The typical mass number of r -elements produced at time t is roughly $A \sim 56 + N_{\text{cap}}(t)$, where $N_{\text{cap}}(t) = \int_0^t n_n(t') \langle v \sigma_{n, \gamma}(\text{Fe}) \rangle dt'$ and where $\langle v \sigma_{n, \gamma}(\text{Fe}) \rangle$ is the rate coefficient for neutron capture on ${}^{56}\text{Fe}$. For zone 597 we find $N_{\text{cap}}(t) = 88$ (226) for $t = 7$ (20) s, which correspond to the shock arrival times for $E_{50} \sim 12$ (1). We conclude, for weak explosions, that the r -process could run to completion in the pre-shock phase.

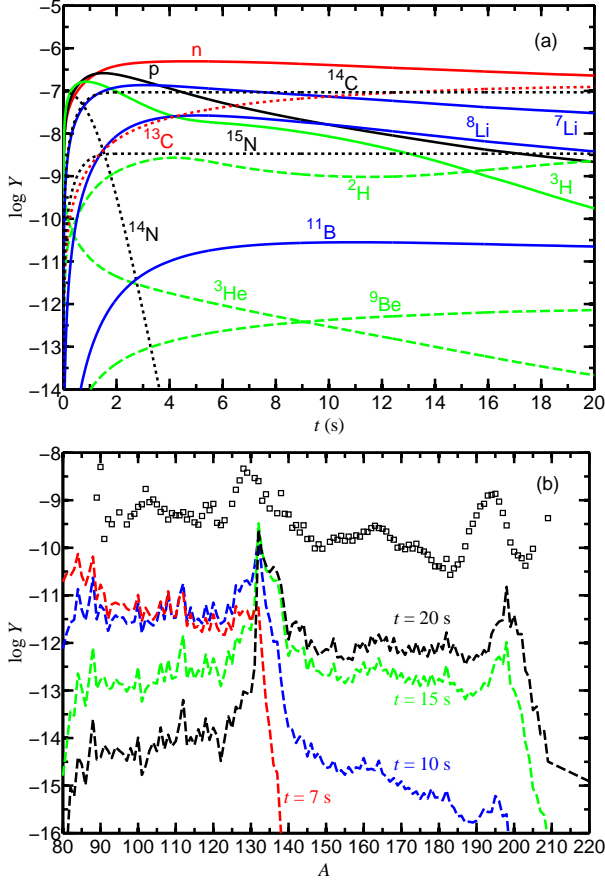


FIG. 1: ν -induced nucleosynthesis in u11, zone 597: (a) Number fractions $Y_i(t)$ of $A < 16$ nuclei; (b) r -process yields at $t = 7, 10, 15$, and 20 s compared to solar r -pattern (squares).

We followed the nuclear flow from ^{56}Fe with a large network Torch [15] that includes all of the relevant neutron capture, photo-disintegration, and β -decay reactions. The yields at $t = 7, 10, 15$, and 20 s are shown in Figure 1b along with the scaled solar r -pattern. The r -process is cold: photo-disintegration is unimportant for He zone temperatures. It is also much slower than usually envisioned. At $t = 7$ s, the r -process flow barely reaches the $A \sim 130$ peak. Significant production of nuclei with $A > 130$ occurs only for $t > 10$ s, and formation of a significant peak at $A \sim 195$ requires $t \sim 20$ s. These times are readily understood. The peaks at $A \sim 130$ and 195 correspond to parent nuclei $\sim ^{130}\text{Cd}$ and $\sim ^{195}\text{Tm}$ with closed neutron shells of $N = 82$ and 126 . With ^{56}Fe as the seed, 74 neutron-capture and 22 β -decay reactions are required to reach ^{130}Cd while 139 neutron-capture and 43 β -decay reactions are required to reach ^{195}Tm . In the absence of photo-disintegration, the r -path is governed by (n, γ) - β equilibrium and the rates for neutron capture and β decay will be comparable. For $\langle v\sigma_{n,\gamma}(\text{Fe}) \rangle \sim 10^{-18} \text{ cm}^3/\text{s}$ and $n_n \sim 10^{19}/\text{cm}^3$, the neutron-capture rate on ^{56}Fe is $\sim 10/\text{s}$. As this

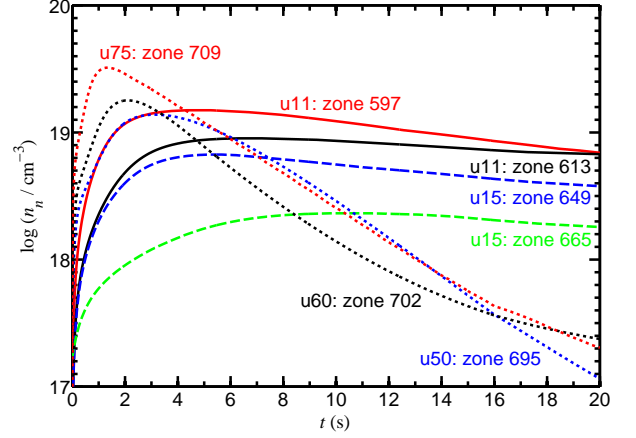


FIG. 2: Neutron number density $n_n(t)$ evolution for selected outer He zones in models u11, u15, u50, u60, and u75.

rate is typical along the r -path, ^{130}Cd and ^{195}Tm will be reached in ~ 10 and 18 s.

We examined other u11 zones and other progenitors. For the IH case with $T_{\bar{\nu}_e} \sim 8$ MeV, neutron densities of $\sim 10^{18}$ – $10^{19}/\text{cm}^3$ are produced in many zones of models u11–u16 and u49–u75. Conditions in u11–u16 are similar to those of zone 597 of u11, but the u49–u75 zones are hotter and denser, $T_8 \sim 2$ – 3 and $\rho \sim 200$ – 600 g/cm^3 . Figure 2 shows $n_n(t)$ for selected zones of u11, u15, u50, u60, and u75. A much higher rate of neutron capture in u50, u60, and u75 leads to more rapid decline of $n_n(t)$. Substantial r -yields are expected in the outer He zones of 11 – 16 and 49 – $75 M_\odot$ stars at $Z \sim 10^{-4} Z_\odot$. An r -process is not expected for stars between 17 and $48 M_\odot$ because the outer He zone has too much hydrogen, a neutron poison.

The total yield of heavy r -elements from each SN is $\Delta M_r \sim 10^{-8} M_\odot$, comparable to $\sim 4 \cdot 10^{-8} M_\odot$ in the Sun. Abundances of heavy r -elements in MP stars with $[\text{Fe}/\text{H}] < -2.5$ are $\sim 3 \cdot 10^{-4}$ – 10^{-1} times those in the Sun [3]. At least some r -enrichments in this range could be produced by an SN in the early interstellar medium, but this process then turns off as progenitor metallicity increases. Both $n_n(t)$ and the $A > 56$ yields decrease significantly with increasing progenitor Z . In the scenarios studied here, r -process conditions are not found beyond $Z \sim 10^{-3} Z_\odot$. Yet net neutron production by ν s is insensitive to metallicity, depending only on SN energy, $\bar{\nu}_e$ temperature, and shell radius, so neutron capture continues on stable seeds like ^{56}Fe , modestly increasing the $A > 56$ yields. The net mass of heavy nuclei continues to be incremented by $\sim 10^{-8} M_\odot$. The associated Galactic chemical evolution [19] should be studied to determine how the ν -driven mechanism might merge into other r -processes, such as NSMs, that may only be viable for $[\text{Fe}/\text{H}] \gtrsim -2.5$ [5].

We have used two separate networks to estimate $n_n(t)$

and the corresponding r -yields. In estimating $n_n(t)$, we adopt a constant neutron capture rate for $A \geq 16$ nuclei. This approximation should be valid because the important neutron sinks ${}^7\text{Li}$ and ${}^{12}\text{C}$ are included, and because the calculations confirm that the total number of neutrons captured per ${}^{56}\text{Fe}$ nucleus is $\ll Y_n$. Nevertheless, future studies should use a complete network for both neutron capture and ν interactions.

The effects of shock passage through the He shell have not been included, though we argued that r -nuclei will survive the associated heating. Other consequences may be beneficial, extending the range for interesting nucleosynthesis. The density of shocked material jumps to ~ 7 times the pre-shock value and then decreases slowly on timescales $\sim \tau_{\text{sh}}$. So while larger explosion energies, $E_{50} \sim 12$, might appear to limit the duration of the r -process to $\tau_{\text{sh}} \sim 7$ s, in fact there may be a post-shock phase where densities higher than those of Fig. 2 aid the nucleosynthesis. Another potentially beneficial effect of the shock may come from neutrons released by ${}^{13}\text{C}({}^4\text{He}, n){}^{16}\text{O}$ and ${}^{17}\text{O}({}^4\text{He}, n){}^{20}\text{Ne}$: ${}^{12}\text{C}$ and ${}^{16}\text{O}$ are the principal neutron sinks in the inner He shell. If shock heating to $\gtrsim 5 \cdot 10^8 \text{K}$ could liberate these neutrons without increasing the abundance of seeds, one might exploit both the more favorable $1/r^2$ of the inner He zone and NC ν channels in neutron production (which in the outer He zone lead to ${}^7\text{Li}$). One source of uncertainty comes from the ${}^{12}\text{C}$ and ${}^{16}\text{O}$ (n, γ) cross sections, which differ by factors of ~ 3 and 45 (10 and 160) at $T_8 \sim 0.85$ (3) between Evaluated Nuclear Data File and Japanese Evaluated Nuclear Data Library [16]. The differences reflect the energy range over which s-wave capture is assumed to dominate. Pending resolution of this discrepancy, parametric studies will be needed [19].

The CC $\bar{\nu}_e$ reaction on ${}^4\text{He}$ plays a crucial role in the ν -induced r -process presented here. The rate of this reaction is quite sensitive to the $\bar{\nu}_e$ spectrum [see Eq. (4)] and thus to both ν emission parameters and flavor oscillations. For our adopted ν emission parameters, only nuclei with $A \sim 70$ –80 can be produced in the outer He zone without oscillations, while no interesting nucleosynthesis occurs for the normal ν mass hierarchy (strong $\nu_e \leftrightarrow \nu_x$ conversion). If we lower T_{ν_x} from 8 to 6 MeV at emission, only nuclei with $A \sim 70$ –80 can be produced even with full $\bar{\nu}_e \leftrightarrow \bar{\nu}_x$ conversion (IH). Recent SN simulations for 8.8–18 M_\odot progenitors yielded significantly softer ν spectra at emission than adopted above [17]. In contrast, spectra similar to ours were obtained for ~ 40 –50 M_\odot progenitors associated with black-hole formation [18]. Recent progress in SN modeling and in the nuclear microphysics governing ν opacity is impressive and should encourage further efforts needed to determine ν temperatures with small error bars.

In conclusion, we have explored one scenario for a cold r -process — the ν -driven He-shell mechanism — as a counterpoint to more conventional high-temperature SN

r -process mechanisms that typically run into problems of seed overgrowth. The ν -induced mechanism is intriguing because it can be evaluated quantitatively in realistic progenitors, and because it is remarkably sensitive to new ν physics. We believe this cold, early mechanism merits investigation in other astrophysical settings, including the inner He zone discussed above and the late stages of ν -driven winds. The mechanism could be part of a multiple- r -process explanation of Galactic chemistry.

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